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EXCITATION CROSS SECTION OF THE $11/2^{-}$ ISOMERIC STATE OF ^{137}Ce NUCLEUS IN (γ, n) REACTION IN THE 11–18-MeV ENERGY INTERVAL OF GAMMA QUANTA

The isomeric yield ratio and the cross section of $^{138}Ce(\gamma,n)^{137m,g}Ce$ reaction in the 11–18-MeV energy interval of γ quanta have been studied on an M-30 microtron using the brehmsstrahlung beam.

Keywords: microtron, cerium, isomeric yield ratio, giant dipole resonance.

1. Introduction

Photonuclear reactions occurring in the energy interval of a giant dipole resonance and accompanied by the emission of various particles in the output channel comprise an important source of information in nuclear physics, nuclear astrophysics, and physics of nuclear reactions. Since the electromagnetic interaction is studied well enough, photonuclear reactions can be used to solve a wide range of problems, such as the precision study of the nucleon-nucleon interaction [1, 2] and the determination of parameters of the giant dipole resonance, by analyzing the partial channels of its decay, including the excitation of isomeric states of daughter nuclei [3].

Till now, the number of regular researches concerning the characteristics of the giant dipole resonance decay through the $(\gamma, n)^m$ channel for nuclei with masses in the interval $A = 120$–140 remained scarce. There are a few works dealing with the cross-sections of $(\gamma, n)^m$ reactions with the barium and tellurium isotopes [4, 5], as well as works, where the isomeric yield ratio $d = Y_m/Y_g$ between the excitation yields for the isomeric, Y_m, and ground, Y_g, states was studied for a number of isotopes and at selected energy points [6].

A need in new improved data for the excitation of isomeric states can be observed in a number of problems belonging to nuclear physics (these are the description of the reaction mechanism, the more precise determination of the distribution function for the level density, and so forth) and allied directions such as the activation analysis and the study of nucleosynthesis processes [7, 8].

It is known from astrophysics that heavy atomic nuclei in stars are mainly synthesized in neutron capture reactions. However, there are several tens of neutron-deficient stable isotopes, the so-called p-nuclei, which are produced by means of a chain of photonuclear reactions. Light cerium isotopes belong to this group. In spite of numerous researches started in this domain, experimental information on the parameters of photonuclear reactions connected with p-processes remains insufficient. Till now, the estimation of the contribution made by p-processes, which is used in astrophysical calculations, is based on the cross-section values obtained with the help of the Hauser–Feshbach statistical model [9]. At the same time, the experimental measurement of the magnitudes of isomeric cross-section (or yield) ratios and the subsequent comparison of the obtained results with the results of model calculations remain one of the effective methods for the verification of parameters in the statistical theory of nuclear reactions, which are based on the model of compound-nucleus decay.

Surely, it should be noted that a considerable body of photonuclear data available for today (including the results of this work) was obtained using the bremsstrahlung gamma beams generated by electron accelerators. A direct result of such experiments is the yields of photonuclear reactions $Y(E_{\gamma\,\max})$. They are connected with the cross-sections of this reaction, $\sigma(E)$, by means of the integral equations

$$Y(E_{\gamma\,\max}) = k \int\limits_{E_{\rm tr}}^{E_{\gamma\,\max}} \sigma(E)\Phi(E, E_{\gamma\,\max})dE. \qquad (1)$$

Here, k is a normalizing factor, $E_{\rm tr}$ the reaction threshold, $E_{\gamma\,\max}$ the maximum energy in the bremsstrahlung spectrum, and $\Phi(E, E_{\gamma\,\max})$ the spectrum of bremsstrahlung gamma emission.

The main purpose of this work was to study the excitation of the $11/2^-$ isomeric state of ^{137}Ce nucleus in ^{138}Ce$(\gamma,n)^{137m,g}$Ce reaction. More specifically, the dependence of the isomeric yield ratio on the maximum energy of bremsstrahlung gamma quanta, $d = f(E_{\gamma\,\max})$, was measured in the interval of energies of the giant E1-resonance. The isomeric state of the daughter nucleus, which is excited in ^{138}Ce$(\gamma,n)^{137m,g}$Ce reaction, is formed by the $h_{11/2}$ subshell, and the ground one by the $3s_{1.2}$ subshell. In this work, the dependence of the isomeric yield ratio on the energy $E_{\gamma\,\max}$ was obtained. This allowed us to calculate the differential cross-section $\sigma_m(E)$ of the isomeric state excitation, determine its parameters (the energy at the maximum, the width Γ, and the effective threshold), and compare the experimental results with the results of theoretical calculations.

2. Experimental Part

The experiment was performed, by using a bremsstrahlung gamma beam generated by a microtron M-30 (Institute of Electron Physics, National Academy of Sciences of Ukraine). The measurements were carried out in the energy interval 11–18 MeV with the step $\Delta E = 0.5$ MeV. The energy of accelerated microtron electrons was varied within two methods. In the wide researched interval, the energy was varied by changing the waveguide insets, i.e. by changing the number of orbits. In order to change the energy in a narrow interval, we varied the magnitude of magnetic field. The magnetic field strength was monitored, by using the nuclear magnetic resonance method. The average current of accelerated electrons was maintained at a level of 5 μA. A tantalum plate 0.5 nm in thickness was used as a braking target. The experimental targets were fabricated from a powder of high-purity cerium oxide (CeO$_2$), which was pressed in the form of disks 20 mm in diameter and 2 g in weight into thin-walled caprolon cartridges.

The activation technique was used in the experiment. The time of the target irradiation by the microtron amounted to 2 h near the threshold of ^{138}Ce$(\gamma,n)^{137m,g}$Ce reaction and to 20 min at energies of 15–18 MeV. The target cooling duration was equal to 20 min. The measurements were carried out for a time period of 22–24 h. The gamma spectra of the induced activity in the irradiated specimens were measured under good background conditions with the help of a gamma spectrometer with a high resolution created on the basis of an HPGe-detector 175 cm^3 in volume and a 8192-channel ORTEC analyzer connected with a computer intended for the data accumulation and processing. The detector resolution amounted to about 2 keV for the 1332-keV line of cobalt-60.

The spectroscopic characteristics of the examined nuclei, which are quoted in Table, were taken from work [10]. In particular, B_n is the threshold of (γ,n) reaction for the parent nucleus ^{138}Ce, J^π the state spin-parity, $T_{1/2}$ the half-life period, $E_{\rm iso}$ the energy of isomeric level, E_γ the energy of the analytical gamma-line, and α the gamma transition intensity.

3. Results and Their Discussion

A section of the experimental apparatus spectrum of a CeO$_2$ specimen irradiated at the maximum energy of the bremsstrahlung spectrum $E_{\gamma\,\max} = 16.0$ MeV is depicted in Fig. 1, where N is the number of pulses in the analyzer channel.

Spectroscopic parameters

Isotope	J^π	B_n, MeV	$T_{1/2}$, h	$E_{\rm iso}$, keV	E_γ, keV	α (%)
^{137g}Ce	$1/2^+$	9.72	9.0	–	447	2.24
^{137m}Ce	$11/2^-$	–	34.4	254	254	10.9

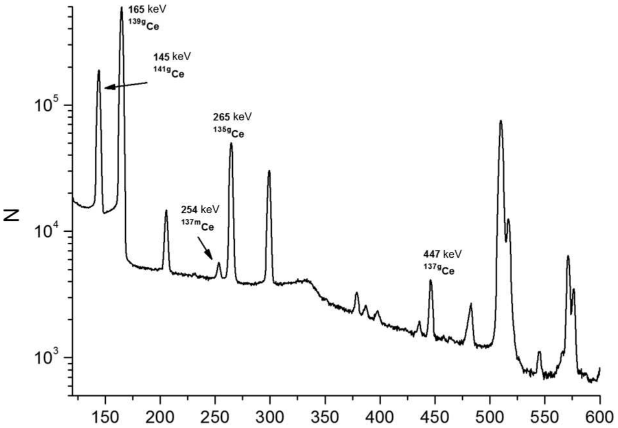

Fig. 1. Section of the experimental apparatus spectrum of a CeO_2 specimen

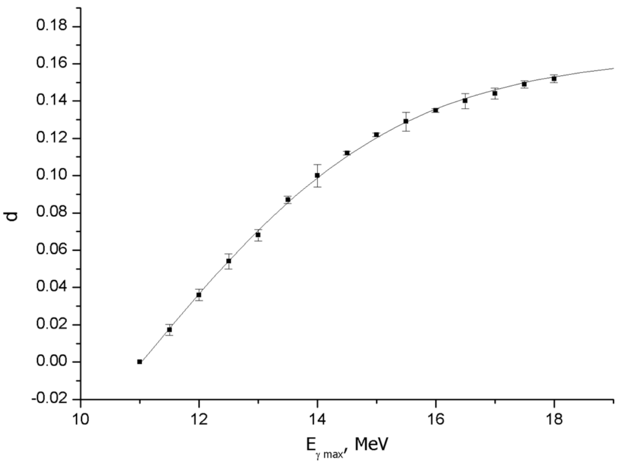

Fig. 2. Experimental yield ratios for $^{138}\mathrm{Ce}(\gamma, n)^{137m,g}\mathrm{Ce}$ reaction

In this work, the isomeric yield ratio d was determined, by using the formula [11]

$$d = \frac{\lambda_g - \lambda_m}{\left\{\left[c\frac{N_g}{N_m}\frac{\phi_m}{\phi_g}(\lambda_g - \lambda_m) - p\lambda_g\right]\frac{\lambda_g}{\lambda_m}\frac{f_m(t)}{f_g(t)}\right\} + p\lambda_m}, \qquad (2)$$

where $\phi_{m,g} = \xi_{m,g}k_{m,g}\alpha_{m,g}$, $\xi_{m,g}$ is the photoefficiency of gamma-line registration, $k_{m,g}$ the self-absorption coefficient for the gamma-line from the decay of the isomeric (m) and ground (g) states, $\alpha_{m,g}$ the intensity of the analytical gamma-lines, N_m and N_g are the numbers of registered pulses from the decay of corresponding states, p is the branching factor, c the coefficient that takes the possible imposing and omitting of pulses into account,

$$f_{m,g} = \left[1 - e^{(-\lambda_{m,g}t_{\mathrm{irr}})}\right] e^{(-\lambda_{m,g}t_{\mathrm{cool}})} \times$$
$$\times \left[1 - e^{(-\lambda_{m,g}t_{\mathrm{meas}})}\right], \qquad (3)$$

is the function of time, $\lambda_{m,g}$ are the decays constants for the isomeric and ground states, and t_{irr}, t_{cool}, and t_{meas} are the durations of the irradiation, cooling, and measurement stages, respectively. The experimental yield ratios $d = Y_m/Y_g$ obtained in such a way for $^{138}\mathrm{Ce}(\gamma, n)^{137m,g}\mathrm{Ce}$ reaction together with the corresponding standard errors are plotted by symbols in Fig. 2. One can see that the isomeric ratio increases above the $(\gamma, n)^m$ reaction threshold and saturates at energies above 18 MeV. The effective threshold of $^{138}\mathrm{Ce}(\gamma, n)^{137m}\mathrm{Ce}$ reaction was experimentally found to equal 11.0 ± 0.25 MeV, which exceeded the (γ, n) reaction threshold by about 1.4 MeV. The solid curve in Fig. 2 illustrates the approximation of experimental data by the Boltzmann curve

$$y = A + \frac{B - A}{1 + e^{\frac{E - E_0}{\Delta E_1}}}, \qquad (4)$$

where A, B, E_0, and ΔE_1 are fitting parameters. The approximation was carried out in the interval 11.0–18.0 MeV in the framework of the least-squares method. As a result, the following parameters were obtained: $A = 0.1651 \pm 0.0014$, $B = -0.1556 \pm 0.0294$, $E_0 = 11.15 \pm 0.36$, and $\Delta E_1 = 2.116 \pm 0.115$.

The measured experimental dependence of the isomeric yield ratio on the maximum energy in the bremsstrahlung gamma spectrum, $d = f(E_{\gamma\,\max})$, made it possible, by using the total cross-sections of (γ, n) reaction [12], to calculate the population cross-sections of the isomeric states, $\sigma_m(E)$. The calculation was carried out, by using the inverse-matrix method with the step $\Delta E = 0.5$ MeV [13]. The results obtained for the excitation cross-section of metastable states of $^{138}\mathrm{Ce}(\gamma, n)^{137m}\mathrm{Ce}$ reaction are exhibited in Fig. 3 by symbols. From Fig. 3, one can see that the cross-section $\sigma_m(E)$ has a single peak with the maximum at 15.5 MeV. The solid curve illustrates the result obtained, while fitting the cross-section σ_m by the Lorentzian curve

$$\sigma(E) = \frac{\sigma_0 \Gamma^2 E^2}{\left(E^2 - E_0^2\right)^2 + \Gamma^2 E^2}, \qquad (5)$$

where σ_0, E_0, and Γ are fitting parameters. The approximation was carried out in the interval $E_0 = 12.25$–17.25 MeV, by using the least-squares method. Ultimately, the following parameter values were obtained: $\sigma_0 = 62.41 \pm 1.27$ mb, $E_0 = 15.36 \pm \pm 0.04$ MeV, and $\Gamma = 3.83 \pm 0.12$ MeV.

In order to compare the experimental results with the theoretical estimations, the cross-sections of $^{138}\mathrm{Ce}(\sigma, n)^{137m}\mathrm{Ce}$ reactions were also calculated with the help of the software package TALYS-1.6 [14]. This package includes the majority of modern models applied for the description of nuclear reactions. The following scenario was used at calculations. A gamma quantum with the energy E_c ($E_c = E_\gamma$) and with a set of possible spin and parity values, (J_c, π_c), is supposed to strike a target nucleus with the parameters (Z_i, N_i) and the spin-parity (J_i, π_i). The total photoabsorption cross-section, σ_{tot}, is calculated. For its description, the experimental parameters of giant resonances [12] are used. The excited nucleus is assumed to decay owing to two processes: following the Hauser–Feshbach statistical mechanism [9] and the mechanism of semidirect processes. In our case, the fraction of semidirect processes amounted to 0.009% at $E_\gamma = 12.0$ MeV, 2.18% at $E_\gamma = 15.0$ MeV, and 6.83% at $E_\gamma = 18.0$ MeV.

In this work, the level density ρ was calculated with the help of the model of Fermi gas with the energy shift [15]. The transmittances T_i calculated in the framework of the optical model [16] were applied to evaluate the spectrum of emitted neutrons, and the transitions on specific excited levels (bands) of the daughter nucleus were considered. In calculations, a spherical optical potential with the Koning–Delaroche set of local parameters [16] was used. At energies below the excitation energy of the daughter nucleus, $E = 3$ MeV, specific discrete levels were taken from the database RIPL-3. In this work, 25 lowest levels from this database [17] were taken into account. At higher energies, the spectrum of excited states of the daughter nucleus was assumed to be continuous (it was divided into 50 energy bands) and described, by using the level density function $\rho(E, J, \pi)$. In the case where the nucleus decays into bands of the continuous spectrum, the average effective transmittance T_l was used for every band.

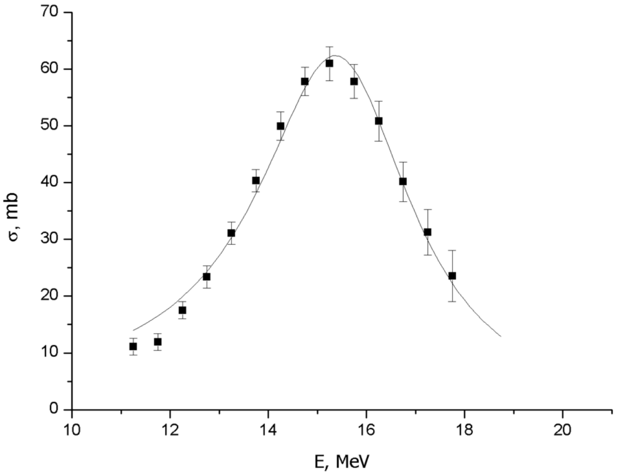

Fig. 3. Excitation cross-sections of metastable states in $^{138}\mathrm{Ce}(\gamma, n)^{137m}\mathrm{Ce}$ reaction

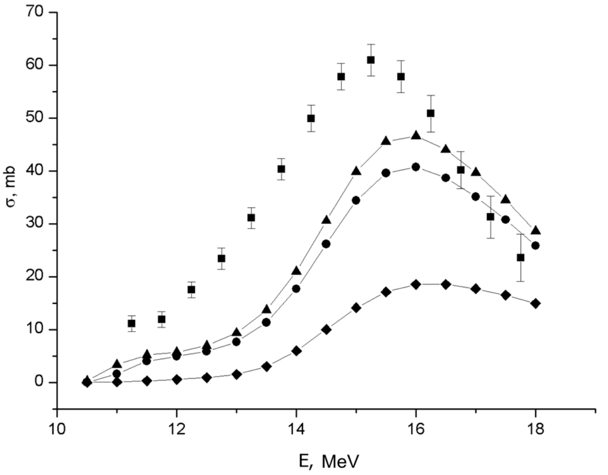

Fig. 4. Comparison of theoretical and experimental cross-sections for $^{138}\mathrm{Ce}(\gamma, n)^{137m}\mathrm{Ce}$ reaction

A comparison of the calculated theoretically and measured experimentally cross-sections in $^{138}\mathrm{Ce}(\gamma, n)^{137m}\mathrm{Ce}$ reaction is shown in Fig. 4. The solid curves correspond to the results of theoretical calculations with the help of the software package TALYS-1; and squares correspond to experimental data. One can see that the direct calculation (diamonds) gives underestimated cross-section values. However, it was demonstrated earlier [5] that the results of calculations of the $(\gamma, n)^m$ reaction cross-sections using the software package TALYS are sensitive to the reliability of the applied low-energy excitation spectra. The analysis of the modern data available for the low-energy excitation spectrum of ^{137}Ce nucleus [17] showed that this spectrum does not contain low-spin levels with negative parities: $7/2^-$,

$5/2^-$, and so on. The spectra of all neighbor even-odd nuclei contain those levels. Moreover, almost for every nucleus belonging to this interval and possessing isomeric states, there exists the $7/2^-$ level, which decays into the $11/2^-$ state. It is most probable that the $(2^+ + h_{11/2^-})$ levels that appear due to the interaction between the vibration 2^+ core state and the one-particle $h_{11/2^-}$ state are responsible for that.

For the direct population of this $7/2^-$ state, neutrons have to escape from the parent nucleus with a momentum not lower than $l_n = 2$. (The corresponding calculations show that the magnitudes of T_l for $l_n = 2$, at which the fraction of such neutrons is equal to a few per cent, appear at a neutron energy of 0.2–0.4 MeV.)

We also calculated the cross-section of $^{138}\mathrm{Ce}(\gamma, n)^{137m,g}\mathrm{Ce}$ reaction provided that the database of low-energy levels would contain the $7/2^-$ levels with energies of 600 and 800 keV. The results of relevant calculations are depicted in Fig. 4 (triangles and circles, respectively). As one can see, the introduction of the $7/2^-$ level with an energy of 600 keV substantially improves the agreement between the theoretical and experimental results.

4. Conclusion

The result of our calculations allowed us to draw a conclusion that the statistical mechanism dominates, when the isomeric state of the examined nucleus is populated. The results obtained also testify that the spectrum of low-energy excitations of ^{137}Ce nuclei has to be determined more precisely.

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ПЕРЕРІЗ ЗБУДЖЕННЯ ІЗОМЕРНОГО СТАНУ $11/2^-$ ЯДРА ^{137}Ce В РЕАКЦІЇ (γ, n) В ІНТЕРВАЛІ ЕНЕРГІЙ ГАММА-КВАНТІВ 11–18 МеВ

Резюме

На гальмівному гамма-пучку мікротрона М-30 в області енергій 11–18 МеВ досліджено ізомерне відношення виходів і переріз реакцій $^{138}\mathrm{Ce}(\gamma, n)^{137m,g}\mathrm{Ce}$.